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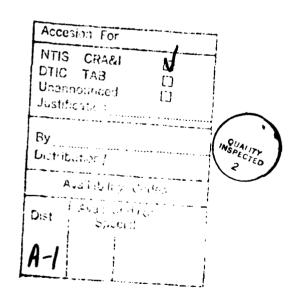
Thomas J. Mueller

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Presentations made at this conference are reviewed. Topics include: airfoil designs methods and verification, airfoil calculation methods, low Reynolds number research at at NASA Langley, unsteady aerodynamic characteristics, wind turbine applications, separation bubbles, experimental facilities and testing, and remotely piloted vehicles.

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CONTENTS

INTERNATIONAL CONFERENCE ON THE AERODYNAMICS AT LOW REYNOLDS NUMBERS BETWEEN 10^4 AND 10^6

1 INTRODUCTION

The International Conference on Aerodynamics at low Reynolds numbers was held from 15 through 18 October 1986 at the Royal Aeronautical Society facility in London, England. Approximately 120 scientists and engineers were in attendance from Europe, Australia, Japan, Bangladesh, and the US. A total of 30 technical papers were presented. An additional five papers were presented as poster papers. Although the international conference concluded on Friday afternoon, an additional session entitled "Practical Aerodynamics Workshop" was held on Saturday morning, 18 October.

The principal objective of this conference was to provide a forum to discuss research results in flow phenomena along with practical engineering problems related to low Reynolds numbers aerodynamics. The applications of this work are related to the design and performance of gliders, remotely piloted vehicles, and microlight, manpowered, and model aircraft as well as to propellers, wind turbines, and other applications. While the conference was designed to attract professional aerodynamicists, both theoretical and applied, the conference was also open to other interested people in this field.

The chairman of the conference program planning committee was Mr. T.J. Patrick of University College, London, UK. Professor John L. Stollery of Cranfield Institute of Technology (UK), a member of the conference planning committee and president-elect of the Royal Aeronautical Society, gave the welcoming address to the participants in order to kick off the conference. In his welcoming remarks Professor Stollery indicated that this conference was put together by enthusiasts and was stimulated by the publication of Martin Simon's book on model aircraft aerodynamics. The review of this book which was published in the Royal Aeronautical Society's magazine *Aerospace*

stimulated a great deal of interest in the UK. He also indicated that Mr. Gates, who organized the model aerodynamics research project in the 1950's, wondered what advances in the design of model aircraft airfoils had been made during the past 30 years. This inquiry brought a response from Tom Patrick, who listed a few of the studies that had been made since the 1950's, and his description ended with the question, "Has the time come to convene another meeting at the Royal Aeronautical Society such as the one the Low Speed Aerodynamic Research Association held in 1953?" The result of that question is the present conference.

Professor Stollery pointed out that the renewed interest in model aircraft aerodynamics coincides with the growth in research related to remotely piloted vehicles and small unmanned aircraft. The designers of such vehicles are having to face the same problems related to transition, laminar separation bubbles, laminar and turbulent separation, hysteresis of aerodynamic forces, and the sensitivity to roughness, to mention the most obvious. There have been a number of recent conferences related to remotely piloted vehicles. One of the most recent conferences which concentrated on airfoil aerodynamics at low Reynolds numbers was the meeting at the University of Notre Dame in June, 1985, organized by Thomas J. Mueller.

A number of the participants in this current conference were at that meeting at Notre Dame and may have looked at this conference as a natural sequel, indicating how much progress has been made in the past year. Both of these conferences were supported by the US Navy Office of Naval Research and in the organizers of this conference would like to thank, in particular, the London Office of ONR for its support and help.

2 AIRFOIL DESIGN METHODS AND VERIFICATION

Aerodynamics at Low Reynolds Numbers

The first paper, by Dr. J.L. van Ingen, Delft University of Technology (the Netherlands), was a review of theoretical

and experimental research at the universities in aerodynamics at low Reynolds numbers. Van Ingen and his colleagues at Delft have been active in this area for many years. They have performed a large number of basic experiments to gain a better understanding of laminar separation bubbles, including transition, which led them to develop prediction methods and finally to the design of low Reynolds numbers airfoils. His paper described the empirical determination of the laminar separation angle--i.e., the angle at which the separation streamline leaves the wall. An extension of the e^n transition prediction method for separated flows as well as a simple bursting criterion for separation bubbles were described. All of these concepts were combined in a simple separation bubble prediction method. This prediction method can be used to design and analyze low Reynolds numbers airfoils.

The second part of this review included a description of experiments which indicated the effects of acoustic disturbances as well as the effects from different types of turbulators on the boundary layer characteristics and the performance of several low Reynolds number airfoils. The low-speed, low-turbulence wind tunnel used was of the closed return type with a turbulence intensity which varied from 0.015 percent at 10 m/s to 0.1 percent at 80 m/s. The lift was measured with a balance system and the drag with a wake rake. Examples where tripping the boundary layer eliminated the separation bubble and reduced the total drag were presented. Studies showing the effects of flap deflection were also included.

Design Techniques for Low-Reynolds Numbers Airfoils

A description was given by Dr. R.H. Liebeck, Douglas Aircraft Company (US), of low Reynolds number airfoil design techniques used at Douglas. He discussed the development of the design methods which have evolved over the past 15 years, and covered the fluid mechanics problem of control of the laminar separation bubble, which is crucial at low Reynolds numbers, along with performance trades between lift coefficient, moment coefficient, Cl_{max}, and thickness-to-chord ratio. A number of airfoils designed by Dr. Liebeck for chord Reynolds numbers below 500,000 were presented along with experimental data comparing the wind tunnel results with the design objectives. The results generally indicated that for chord Reynolds numbers above 300,000 the airfoil performance measured in the Douglas Aircraft Company wind tunnel agree reasonably well with the theoretical predictions.

Wind Tunnel Studies of a Liebeck-Designed Airfoil

Wind tunnel studies of an airfoil designed by Dr. R.H. Liebeck were presented by P. Le Blanc of the University of Southern California (USC). The airfoil geometry studied was the Liebeck LA2573A airfoil section. This model was studied in both the Douglas Aircraft Company's low-speed wind tunnel in Long Beach, California, and the USC Dryden tunnel in Los Angeles. The results presented for this airfoil from the two wind tunnels were comparable. Additional studies of the turbulence intensity in the two wind tunnels indicated that they were the same at 0.1 percent turbulence intensity for frequencies higher than 1 Hz. Low-frequency fluctuations on the order of 20 Hz or less were found to comprise a significant contribution to this turbulence intensity, as indicated by the free-stream velocity spectrum. These results indicated that the measured performance of a given airfoil model in these two wind tunnels, with the same free-stream turbulence intensity, was essentially the same.

Recent Developments in Boundary Layer Computation

Dr. R. Eppler of the University of Stuttgart (West Germany) reviewed recent developments in boundary layer computations which he had included in his design and analysis program. Dr. Eppler has been responsible for a large number of developments in this area over the last 25 years. The program for the design and analysis of low-speed airfoils by Dr.

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Eppler and Dan Somers is the most widely available computer program used for this purpose. The computer program is distinguished by its ability to obtain useful results while employing simple analytical tools. The velocity distribution around an airfoil is calculated using potential flow theory with no provisions made for viscous effects. The boundary layer thicknesses are then calculated for this velocity distribution using momentum and kinetic energy integral methods. The results from the potential flow and boundary layer calculations are then used to predict the airfoil's performance. The lift is estimated using the computed zero lift angle of attack in conjunction with a lift curve slope of 2π. In this procedure it is assumed that the positive effect of airfoil thickness is offset by the boundary layer displacement effects. If turbulent separation is predicted by the boundary layer calculation, the lift is reduced by an amount proportional to the extent of the separated flow. The drag contribution produced by each surface of the airfoil is calculated using the Squire-Young formula. In most cases, the program tends to underpredict the airfoil drag. This is a consequence of the program's inability to estimate the effect of separation bubbles on airfoil drag. In the present paper, Dr. Eppler reviewed the boundary layer techniques used in his computer program and discussed the recent addition of a bubble analogy which attempts to identify those conditions for which the drag penalty, due to a separation bubble, exists. Although the bubble analogy does not account for the effect of a bubble on the external velocity, it treats the flow in the bubble as if it were fully turbulent and is a very helpful tool for airfoil design.

Recent Wind Tunnel Experiments at Low Reynolds Numbers

A paper describing recent wind tunnel experiments at low Reynolds number was given by D. Althaus of the Institute for Aerodynamics and Gas Dynamics at the University of Stuttgart (West Germany). Activities in this field at the Univer-

sity of Stuttgart began in about 1955 under the direction of the late Professor F.X. Wortmann, who died in January 1985. Dr. Althaus worked closely with Professor Wortmann for most of this time in both the design of airfoil sections and in the experimental determination of their performance. Two wind tunnels have been used for these experimental studies.

The large wind tunnel, called the laminar wind tunnel, which was constructed between 1958 and 1960, was especially designed for two-dimensional testing of airfoils. It is an open return wind tunnel with an inlet contraction ratio of 100 to 1 and a rectangular test section 0.73×2.73 m. Chord Reynolds numbers between 300,000 and 600,000 are possible in this facility. The lift of a two-dimensional airfoil section was measured from the pressure distributions on the tunnel walls, the drag was determined from the total pressure loss measured by a wake rake, and the moment of the airfoil was measured by means of a balance. A force balance for measuring lift and drag is also available for this large tunnel.

The smaller model wind tunnel, which is capable of chord Reynolds numbers below 300,000, is also the open return type with a 19.6 to 1 inlet contraction ratio and a rectangular test section 0.37×0.6 m. The reported free-stream turbulence level for this tunnel was lower than 0.075 percent. In this tunnel the lift was measured by a force balance, the drag by a wake rake, the moment by a moment balance.

Althaus presented experimental results for six different airfoil sections designed by Eppler and two airfoil sections designed by Selig. He concluded that hysteresis of the aerodynamic forces at low Reynolds numbers can be caused by two different mechanisms:

1. At low angles of attack it can be caused by transition from subcritical to supercritical flow, or vice versa. Supercritical flow exists when a separated shear layer reattaches at the trailing edge forming a midchord bubble.

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2. At high angles of attack hysteresis can be caused by bursting and reattachment of a laminar separation bubble near the leading edge.

A study of the drag increase due to a 0.5-mm gap in the center of the airfoil model indicated that the additional drag ranged from 5 percent at an angle of attack of 3° to 12 percent at an angle of attack of 9° for a model with a span of 250 mm at a chord Reynolds number of 200,000.

3 AIRFOIL CALCULATION METHODS

Theoretical Aspects of Three-Dimensional Small Disturbances

A third theoretical approach was presented in a paper by Dr. G.R. Inger of Iowa State University (Ames). This paper addressed the theoretical aspects of the formation and properties of spanwise periodic three-dimensional small disturbances in the wake of a slightly stalled wing at low Reynolds numbers. Experimental studies have indicated a small wavy structure on finite wings in the region after stall has taken place. Other examples from surface flow visualization on axisymmetric bodies as well on two-dimensional airfoil models also indicate small spanwise structures. The analysis of the physical events on the boundary layer scale in this paper indicated that the streamwise vortices formed at separation remain distinct and continue far downstream. This implies that the separation-originated vortex structure could produce a spanwise-periodic variation in the drag determination by the wake survey method.

Calculation of Flow Over Low Reynolds Number Airfoils

The paper authored by T. Cebeci, G.S. Wang, and K.C. Chang and presented by Professor Whitelaw of Imperial College, London (UK), covered recent developments in the calculation of flow over low Reynolds number airfoils. The method used was originally developed for high Reynolds numbers flows and was extended so that it could be use to calculate low

Reynolds number airfoil flows. This method is based on the interaction of solutions of inviscid and boundary layer equations and the balance of flow around the airfoil including its wake. The inviscid equations are solved by the conformal mapping technique and boundary layer equations by inverse finite difference procedure. A correlation formula based on linear stability theory was developed and used to calculate transition. The results showed that the accurate prediction of transition was important and was satisfied by the formula used. The paper also demonstrated the need to include the wake in low Reynolds number flow calculations for all angles of attack. A comparison of the results of this calculation technique with experimental results for the Göttingen 797 airfoil at a chord Reynolds number of 700,000 are reasonably good. Another comparison between the calculated lift drag and pressure distribution from this method with experimental results for a NACA 643-418 airfoil at a chord Reynolds number of 300,000 was also reasonably good. The only quantity which did not appear to agree well was the calculation of the drag coefficient. The calculation procedure underestimated the drag coefficient in the low angle of attack range.

Dr. B.R. Williams of the Royal Aeronautical Establishment (RAE) presented a paper on the calculation of flow about airfoils at low Reynolds numbers with applications to remotely piloted vehicles. In this paper, experimental results for five airfoils--NACA 4412, NACA 64$_3$-418, Göttingen 797, Wortmann FX63-137, and GA(W)-2--were compared with calculations obtained from a viscous-inviscid interaction method. Results obtained from this method gave reasonable estimates of the lift and drag coefficients for a number of airfoils down to chord Reynolds numbers of 700,000. The best results were obtained at the higher Reynolds numbers of 1 million or greater for the NACA 4412 and the GA(A)-2 airfoils. As the Reynolds number decreases, the difference between experimental and theoretical value becomes larger. The most notable discrepancies

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between measured and predicted values were for the drag coefficients. These discrepancies were usually related to the inaccurate prediction of the position and mechanism of transition and will increase as Reynolds number is decreased. In order to extend this method to lower chord Reynolds numbers, Williams suggested that several improvements should be made: (1) a more precise calculation of the position of laminar separation, (2) a calculation method for long laminar separation bubbles, (3) a better calculation method for the process of transition, and (4) a better calculation for the separated turbulent boundary layer.

Using the Triple Deck Theory

Two papers concerned use of the triple deck theory. The first, by H.K. Cheng of the University of Southern California (USC--Los Angeles), studied the problem of massive laminar separation, which may be responsible for bifurcating steady-state phenomena. The objective of this approach was to provide some analytical basis for explaining lift hysteresis, symmetry breaking, and other anomalies in the subcritical flow regime. The results of this approach clearly showed the nonunique nature of the steady states of nonlinear, slightly viscous flow.

The second paper using triple deck theory, presented by H. Reed of Arizona State University (Tempe), was a progress report of a continuing analysis of unsteady two-dimensional separation bubbles where the theoretical considerations will be used to match an experiment in a water channel which is under construction. A parallel experimental effort using a low-Reynolds number airfoil in a wind tunnel is also in progress. Preliminary results of this study are encouraging.

4 LOW REYNOLDS NUMBER RESEARCH AT NASA LANGLEY

Research in low Reynolds number aerodynamics at NASA Langley Research Center was reviewed by NASA's W.D. Harvey. NASA Langley has been actively involved in a variety of low Reynolds number aerodynamic research areas in order to increase the data base and also study separation in the hope of improving high-performance flight vehicles and their components. The current emphasis is on the basic understanding of complex flow phenomena which occur at low Reynolds numbers. Several of wind tunnel facilities have been used for these studies. A small, open return wind tunnel called Low Speed Facility, has been used as an inexpensive vehicle to explore a number of low Reynolds number phenomena. This facility has a test section which is 0.3 m by 0.46 m preceeded by a 24 to 1 inlet contraction. The free-stream turbulence level in this tunnel varies from 0.1 percent to 0.25 percent as the chord Reynolds number increases from 80,000 to 400,000. The acoustic disturbance level increases dramatically as the Reynolds number is decreased from about 200,000. The second wind tunnel facility used in these studies was the Langley low-turbulence pressure tunnel, which is a single return, closed circuit tunnel that can be operated at pressures from 0.25 to 10 atmospheres. The test section is rectangular, 0.91 m×2.311 m, and the inlet has a 17.6 to 1 contraction ratio. The low-turbulence pressure tunnel has a disturbance level from 0.02 to 0.06 percent in the chord Reynolds number range from 200,000 to about 1 million per foot. These experimental facilities have been used to evaluate airfoil designs and to study the laminar separation bubbles, boundary layer stability and transition control, and low Reynolds number juncture flows.

Results presented in Harvey's paper showed comparisons between experimental lift and drag characteristics and the theoretical predictions from the Eppler-Somers Code for the Eppler 387 airfoil for Reynolds number from 60,000 to 200,000. While the comparison was quite good for chord Reynolds numbers of 100,000 to 200,000, the lack of separation bubble model in the Eppler code resulted in a large disagreement at a Reynolds number of 60,000.

Lift, drag, pressure distribution, and flow visualization results for the NASA LRN(1)-1007 airfoil were also

presented. It was recognized during the design of this airfoil that the smooth airfoil would have large regions in separated flow and deteriorated performance. It had been anticipated that roughness strips would be necessary to improve the performance of this airfoil. Experimental results comparing the smooth and roughened airfoil surface indicated that at Reynolds numbers from 40,000 to 100,000 the use of roughness did significantly improve the performance of this airfoil. Acoustical tripping of the boundary layer on this airfoil at Reynolds number of 40,000 was also studied. The results of laser Doppler anemometer measurements of a laminar separation bubble in the concave region of an airfoil were also presented. The variation in the boundary layer parameters along the chord indicated a peak in the boundary layer thickness at the position of transition in the free shear layer. A rapid rise in the momentum and energy thickness took place just after this transition point. The transition Reynolds number obtained from these experiments falls in line with data from several other experimental investigations when the transition Reynolds number is plotted against free-stream turbulence levels.

Results from the juncture flow studies obtained in the low-turbulence pressure tunnel were presented with and without corner fillets and with and without three different leading edge fillets. Data showed a secondary flow system on the wing surface near the juncture which can adversely affect the flow over the wings by accelerating trailing edge separation at nonzero angles of attack; the juncture fillet used appears to be an effective way in removing this low-momentum bulge on the curved wing surface. A slight overall flow acceleration in the filleted juncture compared to the no-fillet case still persists. The results of the leading edge fillet experiments indicate that for moderate wing incidence there is some reduction in juncture drag and improved flow characteristics in the wake region for properly designed leading edge fillets. However, care should be exercised since either larger of smaller fillets may produce an overall deterioration in these characteristics.

5 UNSTEADY AERODYNAMIC CHARACTERISTICS

The study of some unsteady aerodynamics characteristics of a NACA 0012 airfoil at chord Reynolds numbers of 125,000, 400,000, and 700,00 was described by M. Fletcher and E. Covert of Massachusettses Institute of Technology (MIT--Cambridge). The Wright Brothers Memorial Wind Tunnel at MIT was used for this study. This wind tunnel is of the closed circuit type with a 2,000-hp motor and a variable pitch fan. The test section is elliptical, measuring 3.05 m along the horizontal major axis and 2.29 m along the vertical minor axis. The length of the test section is 4.57 m. An extensive investigation of the disturbance environment in the test section of this wind tunnel was made. These studies showed that the turbulence intensity varied from 0.7 percent at the chord Reynolds number of 700,000 to almost 3 percent at chord Reynolds number of 125,000. A power spectral density study indicated strong peaks associated with the fan blade passage frequency at about 45 Hz as well as 60-cycle noise and harmonics of each of these. A study of the stability of a laminar boundary layer concluded that none of the high-energy frequencies produced a sufficient amplitude growth to induce transition.

The NACA 0012 airfoil was fixed in the wind tunnel test section and the unsteady flow was produced by a rotating elliptical cylinder downstream of the trailing edge of the airfoil. Unsteady pressure measurements and hot-wire measurements were made. Among the results of this study it was found that the mean pressure coefficient results showed a slight increase in the suction peak, a slight increase in the lower surface pressures, and a slight decrease in the adverse pressure gradient on the upper surface with increasing values of reduced frequency. It was also demonstrated that the unsteady difference pressures decreased with Reynolds number 125,000 and 400,000 but showed no variation above

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400,000. Also, the mean skin friction coefficient decreased with increasing Reynolds numbers as expected. The mean law of the wake results were weakly dependent on the effects of the unsteadiness of the external flow.

6 WIND-TURBINE APPLICATIONS

Wind Turbine Measurements

The paper by B.R. Clayton (University College, London) was concerned with the aerodynamic force coefficients determined from a vertical axis wind turbine simulator. The force coefficients for a vertical axis wind turbine rotor with NACA 0015 and 0020 airfoil sections were determined by integrating the blade pressure distributions. Two constant-section, untwisted airfoils were mounted in the University College vertical axis wind turbine analog rig which was located just downstream from the nozzle of an open jet wind tunnel. The wind speed was held constant at 10 m/s and the airfoils were rotated at speeds between 1 and 4 rps. The version of the paper handed out at the conference contained only three pages. The interested reader is referred to the final proceedings or to the author.

Horizontal Axis Wind Turbines

The presentation by J.L. Tangler and D.M. Somers of Solar Energy Research Institute (UK), concerned a low Reynolds airfoil family for horizontal axis wind turbines. The object of the study was to develop a family of airfoils for horizontal axis wind turbines with rotors 10 to 20 meters in diameter that would perform well at low to medium wind speeds. The performance of these airfoils is enhanced through the use of laminar flow while more consistent rotor operating characteristics at high wind speeds are achieved by tailoring the airfoil so that Cl_{max} is independent of roughness effects. Three airfoil sections consisting of a root section, outboard section, and tip section were designed using the Eppler airfoil design code. Two-dimensional wind tunnel tests were conducted to verify the predicted performance character-

istics of the outboard airfoil, and atmospheric tests of the wind turbine are planned for the future to verify the performance characteristics of the entire airfoil family. The primary airfoil was designed for the radial station 75 percent of the distance from the hub to the tip, while the complimentary airfoils were designed for locations 30 percent from the hub and 95 percent of the distance from the hub. The design criteria for the primary airfoil included high lift to drag through laminar flow, restrained Cl_{max} insensitive to surface roughness, and airfoil thickness of from 12 to 16 percent of the chord. The primary, airfoil designated S805, was evaluated in the Delft University low-speed wind tunnel. A 500-mm chord aluminum airfoil model with 113 chordwise and spanwise pressure orifices was tested at chord Reynolds numbers from 500,000 to 2 million. These tests included the smooth model, called the transition free model, and a transition fixed model using grit roughness near the leading edge. The comparison of the wind tunnel results with those predicted by the Eppler design program were quite good at a chord Reynolds number of 1 million up to about 8° angle of attack for the lift coefficient. At this Reynolds number the drag coefficient comparison showed the same trend although the Eppler design code underpredicted the drag to some degree on the smooth model from an angle of attack of -3° to about 7°. For the rough model, the comparison of the experiment with the theory was quite good from an angle of attack of 2° to about 8°. However, below 2° the Eppler design code overpredicted the drag to some degree. It is clear that in this Reynolds number range the Eppler design code produces airfoil sections which agree reasonably well with the wind tunnel measurements and can be used with confidence.

7 SEPARATION BUBBLES

Using the Viscid-Inviscid Interaction Technique

Another analytical approach, the viscid-inviscid interaction technique for

predicting separation bubble formation on airfoils at low Reynolds numbers, was presented by R.A. McD. Galbraith of the University of Glasgow (UK). While this technique uses empirical methods for predicting transition and reattachment rather than the triple deck theory, it attempts to model airfoil flows in the Reynolds number regime of practical interest. This technique was developed for the prediction of the onset of long separation bubble formation. Comparisons of the predictions with experimental data from one airfoil appeared to be reasonably good. However, the general applicability of the method remains to be shown for a large number of airfoils over a range of chord Reynolds numbers.

A Separation Bubble Experiment

An experimental study of the location of the separation bubble on a NASA LRN(1)-1007 airfoil section using smoke-wire visualization and static pressure distributions was reported by S.S. Fisher and J.D. Abbott of the University of Virginia (Charlottesville). This airfoil section, which was specifically designed for low chord Reynolds numbers, was studied over the Reynolds number range from 60,000 to 220,000 for the angle of attack range from 0° to 16°. The disturbance level and spectrum of the velocity fluctuations in the test section were measured using a single-sensor hot-wire anemometer. The rms fluctuation divided by the mean speed varied between 0.05 percent and 0.1 percent over the speed range from 4 to 24 m/s. The only feature of the frequency spectra which could be clearly associated with tunnel operation was a moderately broad peak which advanced in frequency linearly and increased in intensity with increasing tunnel fan speed. The location of laminar separation, transition, reattachment, and turbulent separation were estimated from smoke flow photographs. Static pressure distributions were also used to determine these locations. Other investigators have found that determining these locations from smoke flow photographs becomes very difficult, especially the location of reattachment. For short separation bubbles

near the leading edge of airfoils, static pressure distributions clearly indicate the location of laminar separation and transition in the separated shear layer. However, reattachment is not always evident or obvious from these data. For long separation bubbles, further downstream on the airfoil, the small gradients in static pressure make it very difficult to determine separation, let alone transition and reattachment.

8 EXPERIMENTAL FACILITIES AND TESTING

An Atmosphere Testing Facility

Dr. H.T. Liu of Flow Research Company, Kent, Washington, presented the results of a rather unusual experimental airfoil study. For this study an environmental aerodynamic test system was developed so that airfoils could be studied with atmospheric disturbances. The system included an instrumented truck, a boom-mounted wing, and an aerodynamic balance mounted inside the wing. The wing profile was that of a Wortmann FX63-137 with a span of 3.66 m and a chord of 0.61 m. Originally, the test system was designed so that experiments could be conducted on a smooth automobile racing track or airport taxi way. By this method one would hope to approach a free flight situation and thus eliminate the interference of confining wind tunnel walls. Preliminary tests, however, showed that the vibration induced by the vehicle motion and by road roughness overwhelmed and masked the effects caused by atmospheric conditions. Thus, it was decided to park the vehicle and face the wing into the prevailing wind in an open field. Because of the unsteady nature of the prevailing wind, the data obtained showed a considerable amount of scatter. Although this study showed that the Wortmann wing did not incur any catastrophic effects due to the unsteadiness of the wind, the data would be difficult to use for any other purpose.

Transition and Separation Control

An experimental study of transition and separation control on the low Reynolds number airfoil NASA LRN(1)-1007 was

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presented by Dr. S.M. Mangalam of AS&M, Incorporated (US). A small, nonreturn low-speed wind tunnel was used for these studies. The turbulence intensity in the test section was determined to be less than 0.25 percent under the test conditions used. The overall background sound pressure level was 87 dB, and this increased with free-stream velocity. No sharp peaks were found in the turbulence or sound pressure fluctuation spectrum. The airfoil model had a chord of 0.1 m and a span of 0.3 m. The airfoil was manufactured with 14 pressure orifices on the upper surface and eight orifices on the lower surface. Lift was determined by integrating the static pressure distributions, and drag was obtained from a 5-cm-long wake rake with 24 nonuniformily spaced total head tubes and a static pressure probe. The wake rake was located three chord lengths behind the airfoil's trailing edge. The design lift coefficient of the LRN1-1007 was 1.0 at alpha = 4° and a chord Reynolds number of 100,000. The design objective was to obtain large lift-to-drag ratios at low Reynolds numbers. The more qualitative data obtained on the same airfoil model by Fisher and Abbott agreed with the data obtained in this study. Since it was assumed during the design of the airfoil that laminar separation would take place, methods of controlling separation were studied. These methods included both surface roughness and acoustical tripping. Two-dimensional surface roughness strips proved to be effective at angles of attack below stall and produced significant improvements in the aerodynamic characteristics of this airfoil. Acoustical excitation was used to influence laminar separation and the frequency and intensity level necessary to do this varied with angle of attack at chord Reynolds number of 40,000.

Accuracy of Low Reynolds Number Wind Tunnel Measurements

T.J. Mueller of the University of Notre Dame (Indiana) gave a paper concerned with low Reynolds number wind tunnel measurements. The emphasis of this paper was on the importance of under-standing the influence of the test facility and instrumentation on the results obtained at low Reynolds numbers. In particular, a method for obtaining two-dimensional aerodynamic force coefficients at low Reynolds numbers using a three-component external platform balance was described. Mueller pointed out that there is an uncertainty in the ability of the experimental facility to simulate a two-dimensional flow environment due to the confinement effect of the wind tunnel walls and the method used to mount the airfoil in the test section. Additionally, the ability of the instrumentation to accurately measure the forces and pressures also has an associated uncertainty.

This paper focused on efforts at the university over the past 7 years to understand the errors introduced by the experimental techniques and apparatus, and on an attempt at estimating the uncertainty of these effects because of the difficulty in making experimental measurements at low Reynolds numbers. The low-speed, low-turbulence wind tunnels used are of the open-return type with a 24 to 1 inlet contraction with 12 screens at the beginning of the inlet. The turbulence intensity is less than 0.08 percent for a bandwidth of 25-2500 Hz. The arrangement used at Notre Dame is to float the airfoil model between two endplates and have the airfoil connected through a shaft to the external strain gauge balance. The endplates are placed some distance from the wind tunnel wall in order to eliminate the thick boundary layer which grows along the wind tunnel wall at low Reynolds numbers. The gap between the ends of the airfoil and the endplates, which is approximately ½ mm, has been shown through a series of experiments not to affect the force measurements in any appreciable way. The major interference effect is the interaction between the boundary layer growing on the endplate and the flow over the end of the airfoil near the endplate. This is a corner-type flow. Although preliminary experiments do not indicate a large interference effect, this problem is being studied in greater detail. The specially designed external platform balance

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has a resolution for the lift force of 0.011 Newtons. The resolution of the drag force is 0.001 Newtons, and the resolution for the torque meter, which measures the moment, is 0.001 Newton-meters. Theoretically, these represent the smallest forces that can be measured. In practice however, the measurement of any force is associated with an uncertainty which must be examined very carefully.

The results of a detailed uncertainty analysis of the lift and drag forces and moment were presented in this paper. The uncertainty depends, of course, on Reynolds number and the value of the force, or moment, being measured. The focus of Mueller's paper was to recognize the limitations in the experimental apparatus as well as the ability of available instrumentation to measure the desired quantities. Discrepancies in results obtained with different wind tunnels, different models, and different techniques may become clear if steps are taken to identify external influences which could alter the results.

Two-Dimensional Characteristics of the NACA 23012

D.I.A. Poll of the College of Aeronautics at the Cranfield Institute of Technology (UK), described the two-dimensional characteristics of the NACA 23012 airfoil in the Reynolds numbers range from 200,000 to 400,000. The experimental measurements were made in the College of Aeronautics Waybridge low speed wind tunnel, which has an open test section, closed-return configuration. The free-stream turbulence level was approximately 0.33 percent at 7 m/s, rising to about 0.4 percent at 20 m/s. The lift forces and pitching moments were calculated from the surface pressure distribution and the drag force was obtained by a wake traverse technique. This study showed that accurate two-dimensional airfoil characteristics can be obtained with endplated models in an open jet wind tunnel. Circular endplates four times the diameter of the airfoil chord were found to be adequate. Accurate two-dimensional data can be obtained when the geometric aspect

ratio of the model exceeds 1.5. In general, these results were consistent with trends indicated in previously published work on this airfoil section.

Surface Roughness Effects

Practical designs require information that is indicative of the performance levels that can be expected from a particular airfoil or wing. Such information is needed not only for smooth sections in benign environments, but also for airfoils operated with accumulated surface roughness which may be caused by dirt, rain, or ice. Data of this type is sorely lacking at low Reynolds numbers. In an effort to provide data of this type, a study of the effect of grit roughness on the performance of the Wortmann FX63-137 airfoil at a chord Reynolds number of 100,000 was performed, and the results were presented by Thomas J. Mueller (University of Notre Dame).

The experiments were conducted in one of the university's low turbulence indraft wind tunnels using 152 cast epoxy airfoils having chords of 152 mm. A smooth model was used for measurement of lift, drag, and moment and flow visualization, and a pressure tap model which was fitted with 40 static pressure taps along the upper and lower surfaces for the determination of the static pressure distributions. Since no proven criteria are available for the selection of roughness height and location in airfoil-type pressure gradients, the transition criterion for three-dimensional roughness given by Klebanoff, Schubauer, and Tidstrom for flat plates was used. This criterion indicated that the critical Reynolds number based on the roughness height and the velocity in the free stream in the absence of the roughness at that location, divided by the kinematic viscosity should be 600. Carborundum and alumina grit attached to double-sided tape were used as a convenient method of attaching the roughness to the airfoil. Three roughness heights were used at a variety of positions along the lower surface near the leading edge, at the leading edge, and along the upper surface at

the pressure section peak, and as far back as the laminar separation point.

The results of this study indicate that the Wortmann airfoil is a high-performance, low Reynolds number airfoil even when operated with roughness and at off-design conditions. The effects of the addition of distributed grid roughness to the airfoil surface are variable depending on the location and height. In general, it was found that roughness located on the forward lower surface, between 1 percent and 3 percent of the chord, had little effect on the performance, except to increase the minimum drag. In contrast, grit located on the upper surface, at or near the leading edge, produced a significant reduction in Cl_{max}. The maximum lift-to-drag ratio, however, could be either improved or degraded depending on the height of the roughness in this region. From the pressure distribution data it was clear that transition can be induced to occur at positions further forward than those at which it naturally occurs. However, it was difficult to bring this transition to the roughness element itself. Therefore, the usefulness of the Klebanoff, Schaubauer, and Tidstrom criteria appears to be questionable since that criteria was developed in order to bring transition to the roughness element.

9 REMOTELY PILOTED VEHICLES

Measurement of Flight Performance of a Remotely Piloted Vehicle

The preliminary measurements of the flight performance of a remotely piloted vehicle (RPV) compared with wind tunnel and CFD estimates was presented by J.L. Stollery (College of Aeronautics at Cranfield Institute of Technology). Previous experimental studies on smooth airfoils in the Cranfield wind tunnel indicated that the FX63-137 had the best performance. The RAE then built a replacement for the X-RAE1 experimental RPV and carried out full-scale tests on half-scale wind tunnel models of the complete vehicle with the original flat bottom wing section and a new replacement wing using the FX63-137 profile. Finally, the RAE

had the College of Aeronautics build a replacement wing for an existing full-scale X-RAE1 in order to carry out flight trials to measure the real performance with the old and new wings.

The conclusions of this very elaborate program indicated that the half-scale model tests of three smooth rectangular wings in the Reynolds number range from 300,000 to 1 million, showed that the Wortmann FX63-137 and the Göttingen 797 sections had very good performance characteristics. The computational model developed by B.R. Williams (discussed above) showed considerable promise in being able to handle the laminar separation, transition, turbulent reattachment, and turbulence separation which frequently occur in this low Reynolds number range. The addition of small amounts of roughness degraded the performance of all three wings. The Göttingen 797 wing section was particularly affected. Overall, the Wortmann wing section was superior. Full-scale tests on a complete model of an RPV clearly showed the advantages of fitting a wing of the Wortmann section rather than the flat bottom section. Using the wind tunnel data, reasonable estimates of the full-scale performance could be made. By inference, Williams' computer program could also have made reasonable measurements down to chord Reynolds numbers of about 700,000. In comparison with the wind tunnel tests and computer calculations, flight trials are extremely difficult. There are almost always likely to be significant differences between the real flight vehicles and even the full-scale wind tunnel models.

Aerodynamics of Unmanned Aircraft

A complete description of the aerodynamics of unmanned aircraft at full-scale in the RAE 24-foot wind tunnel was given by W.J.G. Trebble (RAE). The data obtained in this investigation was used in the previous investigation described by John Stollery. The performances of full-scale models of the X-RAE1 and X-RAE2 unmanned aircraft over the Reynolds number range from 500,000 to 1.2 million were described. The results showed substantial increases in the

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lifting capability by choosing the Wortmann wing section over the flat-bottomed wing section.

Development of a Low Altitude, Low Airspeed, Unmanned Aircraft

The last paper of the conference, presented by Richard J. Foch (Naval Research Laboratory, Washington), described an extensive program to develop low-altitude, low-airspeed, unmanned aircraft. In this paper the preliminary development of a series of designs was described. Design constraints include shipboard storage, long flight endurance at very low speeds, sea-skimming cruise, altitudes, and non-recovery following its mission. Meeting these requirements dictated the development of highly efficient low Reynolds numbers airfoils and advanced airframes and systems. Preliminary designs for aft-tailed twin boom, span-hinged conventional wing/tail, unswept tandem wing, and tip-joined swept tandem wing configurations were described. Selected wind tunnel results were also given. The model sizes corresponded to 0.44 scale for the twin boom model, 0.59 for the joined wing model, 0.345 for the hinged wing model, and 0.44 for the tandem wing model. In this study the simultaneous development and testing of four distinctly different aircraft configurations designed for one set of specifications provided a direct comparison of their aerodynamic qualities under the same experimental conditions. All of these designs showed significant aerodynamic improvements over previous Navy/UAV designs. These improvements were attributed to the use of high aspect ratio wings and the use of airfoils which operate more efficiently in the 100,000 to 500,000 chord Reynolds number range. The aspect ratio and gross weight were the largest factors that influenced the performance of these aircraft configurations. The specific platform configuration, however, did affect stability, control, and handling qualities. Achieving further improvements in aircraft performance over wide speed ranges will require an airfoil of improved performance over a wider range of angles of attack than presently exists. It appears that this

may require airfoils with multiple elements and boundary layer control.

10 MISCELLANEOUS APPLICATIONS

Control Surface Effects at Low Reynolds Numbers

A study of control surface effects at low Reynolds numbers on the Wortmann FX63-137 was presented by J.F. Marchman, III, and V. Sumantran of Virginia Polytechnic Institute and State University (Blacksburg). Two models with different control-surface geometries were used. The Virginia Tech stability wind tunnel was used for these experiments. According to the authors this tunnel has a cataloged free-stream turbulence intensity of 0.02 percent at 15 m/s. The models are mounted on a six-component strain gauge balance strut mounted from the lower surface of the airfoil at midspan of the model. As expected, the lift increased with flap deflection, as did the drag and the moment. Axisymmetric deflections of the control surfaces led to the expected roll moment.

Using Wind Tunnel Data in Design of Model Sailplanes

Martin Simons of the University of Adelaide (Australia) presented a paper concerned with the use of wind tunnel data in the design of radio-controlled contest model sailplanes. The F3B model class sailplanes are judged on three criteria: duration of flight, distance, and speed. The rules limit the sailplanes to a maximum of 1.5 m^2 in total lifting surface area. The maximum allowable mass is 5 kg. The F3B class models are usually slightly under 3 m in span and have aspect ratios between 10 and 15. At the highest speeds encountered, about 30 m/s, with wing chords less than 25 cm, the average chord Reynolds numbers reached by the F3B sailplane wings are somewhat below 500,000. During the low-speed phases of flight, the mean wing chord Reynolds numbers fall below 120,000 and if a tapered platform is used, may be well under 100,000 towards the tips. It is apparent from the low Reynolds number wind tunnel tests that have been performed that the

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theoretical methods used by F.X. Wortmann and R. Eppler do not usually produce accurate predictions below Reynolds numbers of about 250,000. The largest collection of airfoil data available to model designers is that published by D. Althaus from the University of Stuttgart. Simon's paper used the airfoil data from the University of Stuttgart to mathematically examine the changes in important flight parameters as effected by changes in airfoil section.

Propeller Testing

Wind tunnel tests of small-scale pressure-tap model propellers were described by D.W. Hurst and D.T. Owen of the University of Southampton (UK), and P.N. Methven of Dowdy Rotol Limited (UK). The propeller blade was a quarter-scale model of the Dowdy Rotol R292 with a diameter of 0.705 meters and a chord of 0.049 meters at 70 percent of the radius. The blade had 24 chord-wise pressure taps positioned at seven span-wise stations producing a total of 168 static pressure-measuring locations. Blade angles of 14.5° and 25° were used for both two- and four-bladed propeller configurations. A Scanivalve was mounted along the center line of the propeller spinner, and the propeller-spinner arrangement was driven by a 100-hp electric motor. Experiments were conducted in the standard 3.5 m×2.5 m wind tunnel at Southampton and the 2.5 m×1.8 m variable density tunnel at RAE Farnborough. In the propeller arrangement a two-component strain gauge balance was incorporated in order to measure the total thrust and the torque generated. Use of the variable density wind tunnel allowed separate effects of Reynolds number and Mach number to be studied. The propeller apparatus was extensively tested at the University of Southampton and showed that the technique for measuring surface pressure on a rotary propeller could be treated with a high degree of confidence. Both the quality and repeatability of the measurements were considered to be very good within the acceptable experimental accuracy. Experiments at the RAE variable density wind tunnel indicated that models of this size could safely be used to represent conventional full-scale propellers. It was also found that any disturbance in the flow near the blade root spinner junction was found to have a large effect on the rest of the blade because this region has very low local Reynolds numbers.

Prediction of a Microlight Airfoil Performance

A paper entitled "Prediction of a Microlight Biplane's Airfoil Performance Using a Computer Model," which included verification by wind tunnel experiments and flight tests, was presented by P.G. Walton of the Sunderland Polytechnic (UK). This study was based on the MBA Tiger Cub 440 microlight biplane. The purpose of this study was to evaluate the basic airfoil found on the standard airplane. Additional studies were made of a high-lift device and the effect of variable airfoil geometry due to the unstable properties of the fabric used to cover the wings. The lowest chord Reynolds number studied was 900,000. The experimental wind tunnel studies were performed in the Cranfield College of Aeronautics low-speed 8×6-ft wind tunnel using half-scale models of the mono and biplane wings. The theoretical predictions were made by using an airfoil computer program which uses a semi-inverse viscous flow method developed by Williams. Flight tests on the Tiger Cub aircraft were performed in order to confirm some of the theoretical predictions and wind tunnel experiments. To predict trends at lower chord Reynolds numbers, the theoretical method was applied to the standard Tiger Cub airfoil at Reynolds numbers of 6 million, 980,000, and 300,00. The trends obtained from these calculations were what one would expect—mainly, that the separation bubble moves forward and becomes shorter in length at low Reynolds numbers while the separation point remains about the same for all cases. The conclusion of this study indicated that the semi-inverse viscous prediction method, the wind tunnel experiments, and the flight test give similar, although not identical results, for the Tiger Cub airfoil and

its modifications. Although one would expect the flight test to give the most useful results, the effects of small modifications were particularly difficult to determine because slight changes in performance were difficult to measure. Where the semi-inverse program was well calibrated, satisfactory preliminary design studies could be made. The semi-inverse program and the wind tunnel were successful in predicting the effects of making small changes on the Tiger Cub airfoil section over the range of Reynolds numbers considered.

Aerodynamics of the Hang Glider

An experimental investigation of the aerodynamics of the hang glider was the subject of the paper written by M.V. Cook and E.A. Kilkenney (College of Aeronautics, Cranfield Institute of Technology). In the experimental arrangement they used, referred to as the British Mobil Test Facility, the hang glider is mounted on a six-component force and moment balance which is mounted on a superstructure connected to a Citroen CX2400 automobile chassis. The hang glider in this arrangement is about 8 m above the ground. Flow visualization in the form of wool tufts attached to both upper and lower wing surfaces were used to help understand the lift, drag, and moment characteristics measured from the load cells. Results of this study clearly indicate that the extreme flexibility of the hang glider produces nonlinear aerodynamic characteristics. This nonlinearity has, in the past, caused serious stability and control deficiencies at certain flight conditions. A much stiffer structure has evolved to help overcome these problems. No measurements of the atmospheric turbulence intensity or spectrum were made.

Aerodynamics of Gliding Parachutes

J.S. Lindgard (G.W. Defense Equipment, Ltd., UK) presented a paper entitled, "The Aerodynamics of Gliding Parachutes." Because of their ability to cover large horizontal distances from the drop point, and their controllability, gliding parachutes offer considerable advantages for military applications. In this paper, low-aspect ratio wing theory has been applied to establish a mode from which glide performance of the most successful gliding parachutes, the ram air or parafoil, may be better understood. Theoretical predictions were shown to compare reasonably well with the experiments. The optimum performance for a conventional parafoil was shown in this work to be close to a 3 to 1 glide ratio, which agrees with that obtained in practice. Further improvements in aerodynamic efficiency with increasing aspect ratio were shown to be offset by the increased drag of the attachment lines. As a result of this study the next significant move forward in performance of gliding parachute technology appears to be a swept wing parafoil with closed cell ram air and capable of glide ratios exceeding 5 to 1.

Oceanographic Cable Fairing

The development of an efficient oceanographic cable fairing for operation at Reynolds numbers of 250,000 was the subject of a paper by A.R. Packwood (Institute of Oceanographic Sciences, UK), and B.R. Williams (RAE). Oceanographic researchers routinely use towed underwater vehicles for making measurements in the upper layers of the ocean. The depth which such vehicles can be driven depends upon ship speed, length and strength of the tow wire, downforce available at the vehicle, vehicle drag, and cable drag. At ship speeds in excess of 3 to 4 knots it is usually the cable drag that limits the depth which can be achieved. Therefore, it is common practice to put a fairing on the cable. The additional requirement that the cable with its fairing be stored on a large winch drum requires that the fairing be segmented. The purpose of this study was to use both theoretical and experimental techniques to design a fairing whose performance would not deteriorate at low Reynolds numbers--below 1 million--due to flow separation. In order to arrive at a new section shape, a simplified version of the RAE two-dimensional wing section analysis program was used. The simplified

version performs inviscid calculations to determine the force and moment coefficients and pressure distributions for the airfoil at any given incidence. This program then uses the pressure velocity distribution to estimate the boundary layer characteristics including transition, laminar separation and reattachment, and turbulent separation points. This represents only the first iteration of the full method which goes on to recalculate the equivalent inviscid flow and boundary layer characteristics.

Both two-dimensional and three-dimensional wind tunnel experiments were performed on the new, optimized section. A comparison of the numerical predictions in the wind tunnel measurements produced two significant differences. First, the measured drag was significantly higher than that predicted. The reason for this appeared to be that the laminar separation bubble was longer than predicted, with laminar separation slightly ahead of the predicted point. The long separation bubble produced significant modifications in the pressure distribution that was not predicted in the present theory, which is restricted to short, noninteractive bubbles. The second difference was that no fairing stall was evident up to the 10° maximum incidence investigated. This was conceivable due again to the long separation bubble, which meant that the turbulent boundary layer had less distance to run to the trailing edge and was therefore not as prone to separation.

The new fairing, with gaps between the sections, had approximately half the drag of the existing Fathom section and did not exhibit early stall at about 4° incidence, which had been found on the older fairing. The effect of the gaps between the sections of the fairing was smaller than had been anticipated. This increase in drag coefficient due to the gaps had been predicted to be 0.005; and the measured increase was 0.001. The new fairing clearly offered significant performance improvements over the fairing which is currently in use over this Reynolds number range.

11 SUMMARY

A discussion period chaired by Dr. Eugene F. Brown (Office of Naval Research Branch Office, London) followed the presentation of the last paper.

Mueller opened the discussion session by saying that it was evident that a surprising amount of progress had been made since last year's conference at Notre Dame. He was pleased that many people had qualified their wind tunnel disturbance environments by measuring the turbulence intensity and the turbulence spectrum. He went on to express the view that a strong program of basic research in such topics as laminar separation and transition should be continued. The goal of such research should be to provide an experimental data base to guide the development of computational methods. Professor van Ingen indicated his support of this statement and added that calculation of the turbulent boundary layer in the region downstream of the separation bubble was also a basic research topic worth pursuing. Dr. R. Galbraith of Glasgow University issued a plea for standard test case to provide benchmark data by which various computational codes could be compared.

Mueller went on to say that unlike his European colleagues (John Stollery, for example) he could not afford to undertake a research program without financial support. He then expressed a fear that the success of the RPV developments at the US Naval Research Laboratory might give the impression that all the problems in low Reynolds number aerodynamics had been solved and that no additional research was necessary. This view was shared by Professor Fisher. Dr. Liebeck then offered the suggestion that additional support for low Reynolds number research might be obtained if the scope were broadened to include laminar flow control (LFC) work. Professor Inger supported this and added that it should include high-altitude, high-speed flight as well.

Professor Eppler asked when the next meeting would be held and who would organize it. It was agreed that a meeting

in the next 2 years was desirable in order to retain the momentum which had been built up at the meetings over the past 2 years.

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